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THE PROBLEM OF PLASTICITY IN BERYLLIUM¹

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Despite publicized drawbacks (toxicity, high cost), the structural engineer has become more and more aware of beryllium in recent years. The decisive factors in many situations here are the attractive, even unique, properties. A survey of a number of the physical properties of the metal is presented in Table 1. It shows first the lattice structure of beryllium which from the lowest temperatures to near the melting point is crystallized in the most closely packed hexagonal arrangement whereby the axial ratio c/a is somewhat less than the value of $2\sqrt{2/3} = 1.633$, which is the theoretical value for densest sphere packing. This means that the conceptualized spherical atoms in the basal plane are not in contact because the lattice is somewhat widened in this plane. In a restricted temperature range, just below the melting point, a cubic body-centered structure has been observed (Ref. 1).

A high melting point and elastic behavior are associated with lessened density, the elastic behavior being distinguished by a modulus of elasticity higher than that of steel. The transverse contraction coefficient is strikingly low. The table contains, on the basis of the values obtained in single crystal experiments, the parameter of elasticity parallel and perpendicular to the hexagon axes. Finally, in the table the macroscopic absorption cross section for thermal neutrons is presented, which is the lowest of all structural materials in question for the building of reactors.

This superiority of the structural material beryllium, with respect to neutron permeability, is particularly important as a figure of merit defined as the quotient of tensile strength over macroscopic absorption cross section. Figure 1 gives the temperature dependency of the figure of merit thus defined for various reactor materials. The most favorable combination of density, temperature resistance and strength opens to beryllium a burgeoning field of application in aircraft construction, and in the building of rockets and satellites. The low neutron absorption cross section in combination with good heat resistivity and good

¹Lecture to the Fourth International Light Metal Congress, Leoben, June 1961.

Table 1. Physical properties of beryllium

Lattice constants

 α -Be (close packed hexagonal) at 20°C

$$\begin{aligned} a &= 2.281 \text{ \AA} \\ c &= 3.577 \\ c/a &= 1.568 \end{aligned}$$

 β -Be (cubic body-centered) at 1250°C

$$a = 2.55 \text{ \AA}$$

Density α -Be at 20°C

$$1.848 \text{ g/cm}^3$$

Melting point

$$1284^\circ\text{C}$$

Thermal arrest, transformation $\alpha - \beta$

$$1245^\circ\text{C}$$

Modulus of elasticity

$$\begin{aligned} E_{||} &= 37,400 \text{ kp/mm}^2 \\ E_{\perp} &= 28,000 \text{ kp/mm}^2 \end{aligned}$$

Poisson's ratio

$$\begin{aligned} \mu_{||} &= 0.10 \\ \mu_{\perp} &= 0.035 \end{aligned}$$

Macroscopic absorption cross section

$$\Sigma_a = 0.0012 \text{ cm}^{-1}$$

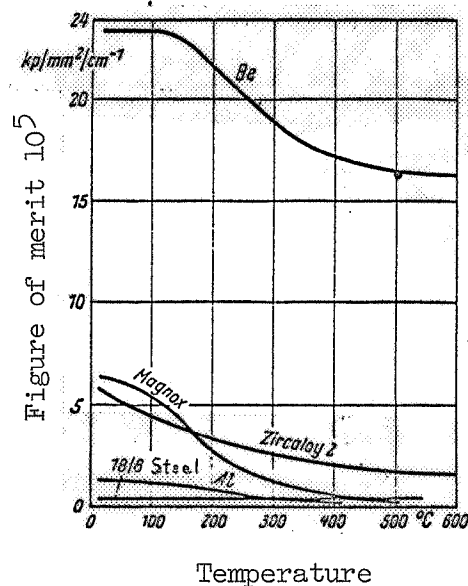


Figure 1. Temperature dependency of a figure of merit of reactor structural materials

compatibility with uranium as well as favorable corrosion behavior with respect to metallic melts (bismuth, alkali metals, etc.) makes it a valuable structural material for thermal reactors.

A circumstance in addition to the mentioned disadvantages of beryllium still stands in the way of its use. This is its brittleness, which makes noncutting shaping and technical assembly difficult. Repeatedly for this reason there has been a changeover to powder metallurgical techniques. Figure 2 shows the temperature dependence of the length value of tensile strength and expansion of hot pressed rods starting in one case with vacuum cast bolts and on the other hand with "QMV" powder.¹

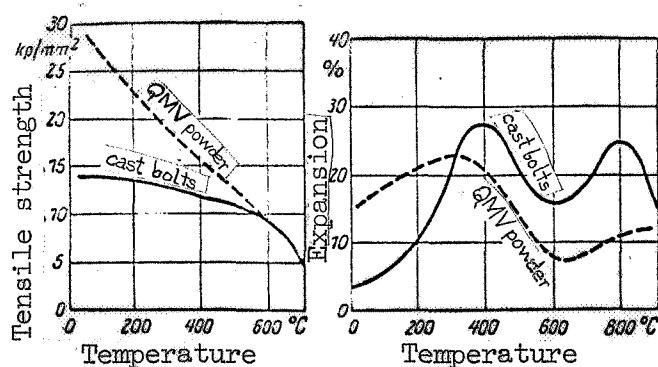


Figure 2. Temperature dependency of tensile strength and expansion of hot pressed beryllium rods (Ref. 2)

It will be observed that at lower temperatures the fine grained samples produced by powder compaction are by far superior to those taken from cast material. Above all, it is to be noted that the room temperature expansion of rods pressed from cast billet is very low. With rising test temperature it increases substantially without, however, equalling that of the expansion of powder compacted rods. The present report is concerned with the discussion of beryllium brittleness demonstrated with reference to an example. Two aspects are to be considered primarily:

1. The mechanism of crystallographic deformation and the dynamic conditions² that prevail; and

¹Magnesium reduced beryllium is for this purpose cast in vacuum, chipped and ground to a powder.

²Although in beryllium even at the relatively low temperature of 400°C there are indications of grain boundary plasticity, this factor only at very much higher temperatures (800°C or above) limits the technical applicability of the material.

2. The degree of purity of the material, especially the question of formation of mixed incorporation crystals.

Figure 3 characterizes the effective slip and twinning mechanism. ✓ Slip occurs on the basal plane and on the prismatic plane of the first class. In both cases the bottom edge of the basal hexagon is the effective direction of slip. Mechanical twinning occurs with a pyramidal surface of the first class, second order ($10\bar{1}2$), as glide plane (first circular section plane), and a $(10\bar{1}1)$ direction as polar glide direction η_1 (second circular section plane K_2 also a pyramidal surface I.A.2.O. ($10\bar{1}2$)). Displacement amounts to 0.186.

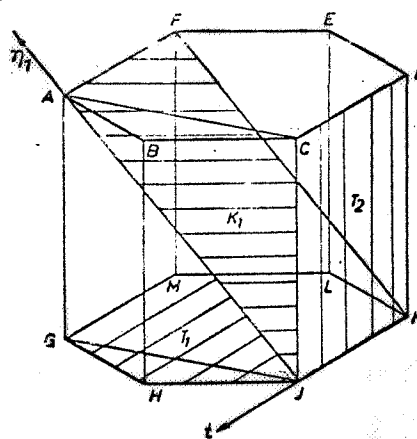


Figure 3. Glide elements and planes of cleavage of beryllium crystals (see Ref. 3)

Glide along prismatic planes of the first class is observed in all metals that have a hexagonal sphere packing of maximum density, somewhat compressed, in the c-axis (Be, α -Ti, α -Zr). Cleavage is observed in beryllium crystals along the basal plane and a prismatic plane of the second class ($11\bar{2}0$). Figure 4 shows as an example of prismatic plane slip, a crystal which has developed a cutlike neck as a result of duplex prismatic glide, and Figure 5 shows an example of basal cleavage. /2

Critical shear stress of the glide system serves to characterize slip. Figure 6 shows the temperature dependency of this critical shear for basal and prismatic glide for crystals having a degree of purity of about 98.9 percent. It is to be observed that the critical resistance to shear of the base increases slightly at first with the temperature. After 500°C the critical shear resistivity of the base practically coincides with that for prismatic glide, which at first was considerably higher, but which drops steeply with increasing temperature. An

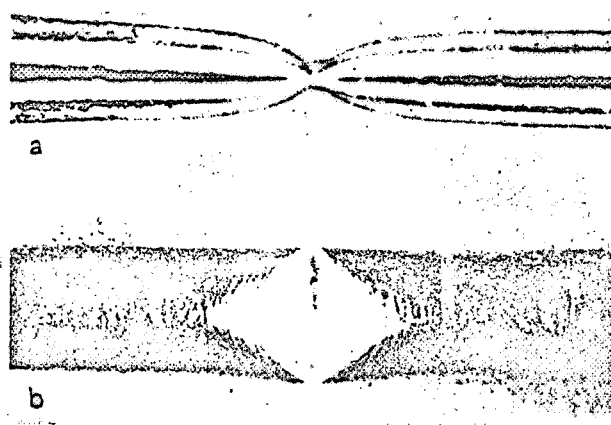


Figure 4. Duplex prismatic glide in a beryllium crystal (Ref. 4)

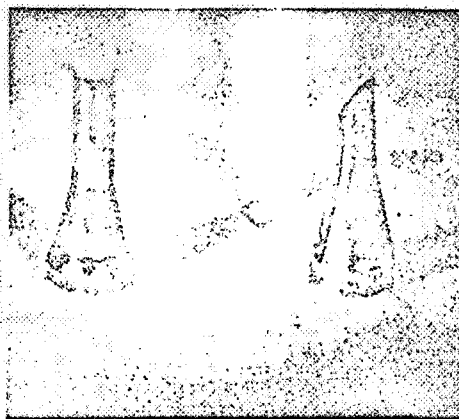


Figure 5. Basal cleavage of a beryllium crystal (Ref. 5)

indication of critical normal stresses for cleavage surface will be presented later. With rising temperature, the inclination to twinning, as well as the tendency to cleavage along crystal planes, declines.

The texture deformations occurring in the blank after noncutting shaping can plausibly be interpreted on the basis of changes of orientation connected with the shaping operation. It may be mentioned as an example that in extruded rails, the basal plane is preponderantly

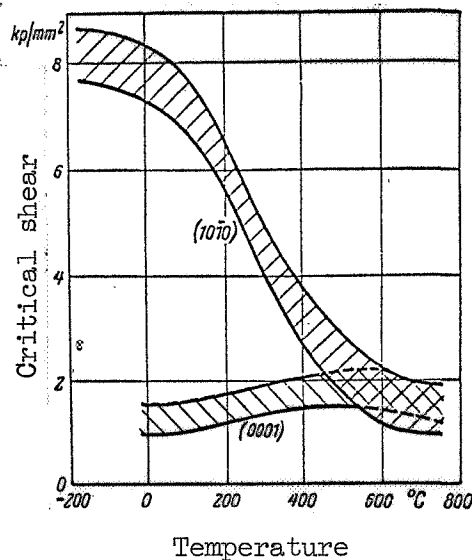


Figure 6. Temperature dependency of critical shear of basal prismatic glide system of beryllium (Ref. 4)

perpendicular to the transverse direction of the rail. With cross rolling of the rails there can be attained only a texture that is nearly rotation-symmetrical about the sheet normal with base in the plane of the sheet. If the total reduction of the cross rolling exceeds a certain value, an area of scatter appears which is now perpendicular to the plane of the pressed rail. These deformation texture changes lead to remarkable changes in the technological properties of strength. Figure 7 shows the expansion in the rolling and transverse directions as a function of total reduction.

While in the pressed rails there is an extraordinarily strong anisotropy of expansion (parallel to future direction of rolling--transverse to the rail--the expansion is practically zero), with reduction the expansion in rolling and transverse direction first increases substantially, passing at 83 to 93 percent rolling reduction through a rather uniformly flat maximum. It declines again as the rolling reduction ratio increases, whereby now the transverse expansion decreases more sharply than in the rolling direction.

In the illustration, basal pole figures are also shown schematically for as-extruded rails and for rolling reduction ratios of 90 to 96 percent, which show the above noted change of the area of scatter. By selection of suitable cross shaping that can be related not only to an extruded rail, but also to a single rolled sheet, it is possible, therefore, to achieve a good expansion value in all directions in the plane of the sheet.

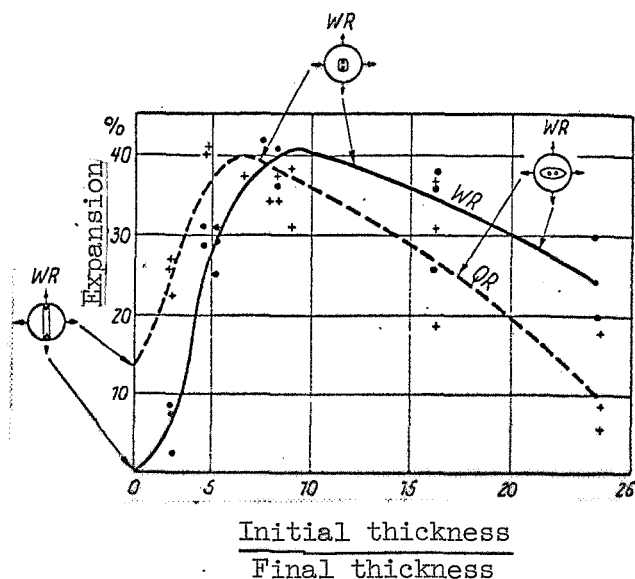


Figure 7. Concerning development of "two-dimensional" plasticity in beryllium sheet (Ref. 6)

Absolute brittleness perpendicular to the plane of the sheet is the price. This behavior is immediately understandable on the basis of the "two-dimensional" plastic texture in this state. Basal slip and basal cleavage are excluded in the plane of the sheet because of the principal basal orientation with not too excessive scatter. Deformation results from prismatic glide for which, in all directions of the plane of the sheet, favorable starting positions of the glide elements exist. For a deformation perpendicular to the plane of the sheet, except for basal slip, prismatic slip is also excluded. Moreover, with a pressure stress the formation of deformation twins with $K_1 = (10\bar{1}2)$ cannot occur in that

this polar displacement mechanism leads only to an elongation in the hexagonal axis, and not to a contraction.

In samples similarly obtained by cross rolling, it was determined that fracture results in the plane of the main axis $(11\bar{2}0)$. For the relationship of true tensile strength, parallel to the rolling direction, to the corresponding value in the perpendicular direction thereto, the value 0.752 was determined. Since essentially there exists a texture with basal plane parallel to the plane of the sheet with a double axis of the first class in the rolling direction, this means that fracture on $(11\bar{2}0)$ occurs when a constant normal stress in this fracture plane is reached (Ref. 7).

For evaluation of the danger of fracture of beryllium crystals on the basis of Sohncke's law of normal stress, it is to be pointed out that doubts have recently been raised concerning its validity, which was judged to have been confirmed in a series of ionic and metallic crystals (Ref. 8). In expansion experiments with thick zinc crystals at -196°C , the tension stress necessary for rupture along the basal plane rose surprisingly in contrast to the requirement of the law of normal stress, if the angle of inclination towards the lengthwise direction increased from 45 to 90° (Ref. 9).

Instead of a critical normal stress dependent upon the basal slide preceding the rupture and upon the experimental temperature, there is in Ref. 10, for hexagonal metal crystals with basal cleavage, a condition of fracture proceeding from the rupture along the base:

$$\tau_s - \tau_0 = \frac{k \cdot \cos \chi}{\sigma_n}$$

(τ_a and τ_0 are the shear stress in the basal slide system at the start of expansion and at the start of the fracture; χ is the angle between the direction of tension and the basal plane; σ_n is the normal stress on the base at the moment of rupture; k is a constant that depends essentially upon the elastic parameters and surface energy, and which is practically independent of crystal orientation).

There are not as yet any extensive experimental results with which to check the validity of the formula for beryllium crystals. It will be recognized, however, that in crystals with slanted starting position of the basal plane, a more pronounced deformation can be anticipated than in "cross" oriented crystals. The same result is obtained also with the law of normal stress. According to it, a rupture along the basal slide plane after prior slip will only result if a certain minimal stabilization is present which overcompensates the rupture tendency that accompanies expansion by reorientation. Which of the fracture conditions should be assigned priority can only be cleared up by further experiment.

Though success is also attained by special procedures in developing satisfactory ductility in the plane of the sheet in the course of sheet manufacture, the problem of beryllium brittleness is still not solved by any means. It is only the optimum for a special case on the basis of the special deformation and cleavage mechanisms of beryllium. For a more general elimination of brittleness, there must primarily be a combating of the tendency to form dangerous cracks along the basal plane.

Of special interest in this connection are experiments which test the significance of the degree of purity for the plastic deformation of beryllium single crystals. By zone melting up to an eighth repetition,

the impurities in the starter material were constantly reduced. As a result of the experiment, Table 2 presents data on critical shear, expansion and boundary slip of crystals with a starting position of the basal plane at 45° to the direction of tension. The critical shear resistance of the base was reduced to one-fifth by thorough purification of the material, as was the expansion, which in impure crystals was less than 1 percent and increased to 100 percent in the purest crystal. Fracture of the crystal occurred through basal cracking (see Figure 5). Suitable analyses of the impurities are not available.

Table 2. Basal glide in zone melted Be crystals (Ref. 11)

Number of zone melts	Critical shear p/mm^2	Expansion %	Glide %
0	1750	< 1	< 2
2	1225	8.1	18
8	350	100	160

A mass of evidence indicates that the importance of metallic impurities which lead to substitution mixed crystals are without great influence on the behavior of the beryllium crystal. For this reason it would hardly be possible to go wrong if the extraordinarily great effect is ascribed to a reduction of metalloid content (especially oxygen) through purification. The importance of oxygen content for beryllium brittleness has repeatedly been indicated. The beryllium oxygen diagram is not yet known. It is certain that the solubility of oxygen in beryllium is slight. The embrittlement is mostly attributed to the formation of a Be-BeO eutectic, which is present as grain boundary in the polycrystal and may be responsible for intercrystalline fracture.

In order to interpret these zone-melting experiments with single crystals, it is necessary to think primarily of oxygen dissolved in the beryllium. Undoubtedly because of the great difference of atom diameter it is a question of incorporated mixed crystals whereby the oxygen presumably has been incorporated in octahedral, interlattice spaces on $1/8$ or $3/8$ of the c axis (see Figure 8). Therefore, disturbing interlayers parallel to the basal plane occur which reduce stability perpendicular to the base and which, therefore, increase the cleavability along this plane. It seems understandable, moreover, that critical shear resistance of the base will be increased by the incorporated foreign atom layers. If, on this account, the oxygen content were reduced by repeated zone melting procedures (for which observations concerning surface separation of BeO during the melting would yield reference points), the lowering of the limits of ductility of the crystal and the increase of the

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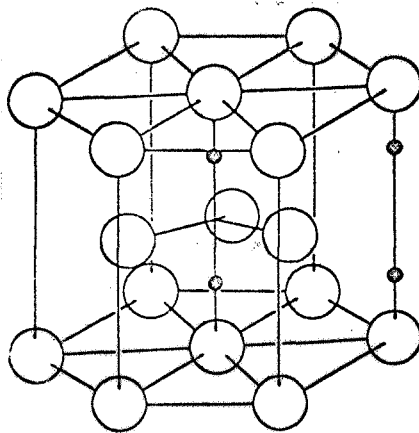


Figure 8. Octahedral interlattice spaces in the beryllium lattice

deformation that can be induced in tension experimentation would be plausibly explained.

Both crystallographic mechanisms and impurities seem, therefore, to be responsible for the brittleness of beryllium. A combating of brittleness will primarily be undertaken by the greatest possible purification of the metal, particularly with respect to metalloids (oxygen). This measure, not only in order to prevent the formation of an oxide-encasing shell around the grains of the polycrystal, but also in order that the tendency, therefore, to crack-formation along the basal plane, which occurs at very low stresses as cleavage along prismatic planes of the second class, can be reduced by preventing the formation of basal interlayers.

Which purification method, zone melting, high vacuum distillation or alkali reduction of beryllium halides, is preferably left to the future. If this improvement is successful, it will then be possible to consider making sheet with two-dimensional plasticity deformable also in the third dimension by the introduction of twinning layers in which secondary translation permits deformation also in the direction of the sheet normal. The enforced twinning could perhaps be effected in the same way, as has already been done successfully for a long time in the case of magnesium sheet with a roll texture similar to that of beryllium sheet, that is by alternate extension and compression of the sheet parallel to the plane of the sheet by repeated passes through straightening rolls (Ref. 12).

A type of notch effect, also crystallographically-conditioned, will in any case remain in the purified metal. For the occurrence of this

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type of notch effect in beryllium there are no sure data. It depends on the formation of Rose's cavities, which occur in multiple twinning at the points of intersection of the layers.

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